

DESIGN, MANUFACTURING AND TESTING OF PARACHUTE RECOVERY
SYSTEM FOR ALUDRA SR-10 UNMANNED AERIAL VEHICLE (UAV)

RAUDHAH BINTI SAIM

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2019

ACKNOWLEDGMENT

Assalamualaikum w.b.t

In the name of Allah, the Most Generous and the Most Merciful

It is impossible to look back on this thrilling journey without thinking of the many great people that have contributed directly or indirectly to my work and the completion of this thesis. First of all, I would like to express my profound gratitude to my supervisor, Dr Sofian Bin Mohd and co-supervisor, Dr. Syariful Syafiq Bin Shamsudin, for their valuable support, encouragement, supervision and useful suggestion throughout this research work. Their moral support and patiently guidance enable me to complete this project.

My thanks also go out to the support I received from the collaborative work I undertook with the Unmanned Systems Technology Sdn Bhd (UST), Selangor, during the first phase of my field work – thank you to Mr. Muhammad Riza Abd Rahman and all his staff who were always so helpful and provided me with their assistance throughout my dissertation.

To my colleagues, staff and lecturers in the Faculty of Mechanical and Manufacturing Engineering, highest appreciation and thanks for their helps and suggestion regarding to this project.

I am as ever, especially to my beloved parents, Saim Bin Mohamed and Zalekha Binti Abu Talib for their love, endless moral support and encouragement throughout my life. I am also thankful to all my siblings who guide me about the path of life. Your contribution and sacrifices will always remember.

ABSTRACT

Unmanned Systems Technology (UST) Aludra SR-10 Unmanned Aerial Vehicle (UAV) was purposely designed for survey and mapping mission. This study focuses on the design, manufacturing and testing of Parachute Recovery System (PRS) on the Aludra SR-10 UAV. A design work of PRS involving in defining a suitable type of parachute design, parachute compartment, parachute deployment and activation mechanism system. This study was performed by simulation approach (using Computational Fluid Dynamic, CFD) and experimental approach (static drop test and flight test). The evaluation of aerodynamics characteristics using ANSYS software over two types of parachute models (annular and cruciform parachutes canopy) help to determine the most suitable type of parachute design for PRS. The static drop test with on board system (consisted of NI myRio, IMU and GPS) programme using LabVIEW software was performed to evaluate the feasibility of the parachute. Meanwhile, the flight test was conducted to investigate the performance and reliability of PRS at different deployment heights. A baseline annular parachute canopy with 2.41 m of the nominal diameter was selected as the main parachute, which produced highest drag coefficient (1.03). The findings also highlighted the significance of separation and recirculating flows behind studied geometries, which in turn was responsible in producing the drag. Through the static drop test, the selected parachute design provided a predicted terminal descent velocity of approximately 4 m/s with payload of 5kg. This parachute recovery system was able to reduce the impact force at fourth time lower compared to belly landing, from 139.77 N to 30.81 N. The pilot-chute was successful pulled main parachute to free stream and fully inflated in a short time, less than 3 seconds. Most of all, the parachute recovery was able to support and bring the aircraft to a soft and safe landing thus, confirmed its reliability. Interestingly, robust evidence in a prediction of the landing position area using PRS was achieved.

ABSTRAK

Unmanned Systems Technology (UST) Aludra SR-10 Unmanned Aerial Vehicle (UAV) adalah direka bagi tujuan misi kaji selidik dan pemetaan. Kajian ini memberi tumpuan kepada reka bentuk, pembuatan dan ujian Sistem Pemulihan Parasut (PRS) pada Aludra SR-10 UAV. Reka bentuk ini melibatkan kerja untuk menentukan jenis payung terjun yang sesuai, tempat penyimpanan payung terjun, sistem terjun payung dan sistem mekanisme pengaktifan. Kajian ini dilakukan dengan pendekatan simulasi (menggunakan Computational Fluid Dynamic, CFD) dan pendekatan eksperimen (ujian penurunan statik dan ujian penerbangan). Penilaian ciri-ciri aerodinamik ke atas dua jenis model payung terjun (berbentuk annular dan cruciform) dengan menggunakan perisian ANSYS menunjukkan bahawa payung terjun berbentuk annular yang paling sesuai diunakan sebagai PRS. Ujian pelepasan secara statik bersama sistem yang dilengkapi dengan perisian LabVIEW digunakan untuk menguji dan menganalisis trajektori payung terjun. Sementara itu, ujian penerbangan telah dijalankan untuk melihat kebolehpercayaan pelaksanaan PRS di Aludra SR-10 pada ketinggian yang berbeza. Payung terjun berbentuk annular dengan garis pusat kira-kira 2.41m dipilih sebagai payung terjun utama kerana ia menghasilkan pekali seret yang tertinggi (1.03). Simulasi ini menunjukkan aliran di sekeliling geometri, yang bertanggungjawab untuk menghasilkan daya. Melalui ujian penurunan statik, reka bentuk payung terjun yang dipilih memberikan kelajuan penurunan terminal kira-kira 4 m/s dengan muatan 5kg. Sistem pemulihan payung terjun ini dapat mengurangkan empat kali ganda daya impak semasa mendarat berbanding pendaratan perut pesawat, dari 139.77 N hingga 30.81 N. Pilot-chute berjaya menarik payung terjun utama untuk aliran bebas dan melambung sepenuhnya dalam masa yang singkat, kira-kira 3 saat. Pemulihan payung terjun mampu menyokong dan membawa pesawat ke pendaratan yang lembut dan selamat. Di samping itu, kajian ini dapat memberikan bukti kukuh untuk meramalkan kawasan pendaratan yang menggunakan pemulihan payung terjun.

LIST OF ABBREVIATIONS

AGL	Above ground level
C.G	Center of gravity from the aircraft
CFD	Computational Fluid Dynamic
CTOL	Conventional take-off and landing involving the use of runways
GCI	Grid Convergence Index of the meshing
GSC	Ground Control Station
IMU	Inertial Measurement Unit
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LOS	Line of sight
NI	National Instrument
PRS	Parachute Recovery Systems
PWM	Pulse-width modulation
RANS	Reynolds-averaged Navier-Stokes
SUAV	Small Unmanned Aerial Vehicles
TRANS	Time Reynolds Averaged Navier-Stokes Equations
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VTOL	Vertical take-off and landing that can take off and land vertically.

LIST OF SYMBOL

μ	Viscosity of air	kg/m.s
Δs	Prism layer thickness (Inflation)	mm
b	Drag coefficient exerted on the aircraft cause by air resistance	-
C_d	Drag coefficient	-
C_l	Lift coefficient	-
d	Drag coefficient exerted on the parachute cause by air resistance and the aircraft	-
D_c	Constructed diameter of parachute	m
D_o	Nominal diameter of parachute	m
D_p	Inflated shape projected diameter of parachute	m
D_T	Total drag of the parachute and the aircraft/load	N
D_v	Spill hole diameter of annular parachute	m
F_{Impact}	Impact attenuation upon landing	N
g	Acceleration of gravity	m/s ²
h	Inflated height of fully inflate parachute	m
H_{Loss}	Altitude loss during inflation process	m
L_{arm}	Cruciform arm's length	m
L_e	Suspension line length of parachute	m
n	Filled constant of parachute during inflation process	-
q	Dynamic pressure	-
Re	Reynolds number	-
S	Cross sectional area	m ²
t_f	Parachute inflation time	s
V_f	Final velocity of the aircraft	m/s
V_t	Rate of descent during recovery	m/s

w	Cross wind speed	m/s
W_{arm}	Cruciform arm's width	m
W_{Chute}	Weight of parachute	N
W_{Load}	Weight of aircraft/load	N
W_T	Total weight of the parachute and the aircraft/load	N
ρ	Density	kg/m ³



LIST OF FIGURE

2.1	Forces act on the parachute during parachute recovery	10
2.2	Airflow around open parachute canopy	11
2.3	Airflow and stability for various parachute design	12
2.4	Parachute sizing chart	17
2.5	Annular parachute canopy configuration design	19
2.6	Cruciform parachute canopy configuration design	20
2.7	Cruciform parachute application	23
2.8	Phoenix Jet Target drone parachute recovery process	24
2.9	ZOCP-JET2 target drone parachute recovery process	25
2.10	Fixed-wing TuffWings UAV	25
2.11	I-View UAV	26
3.1	Aludra SR-10 Unmanned Aerial Vehicle	28
3.2	Communication systems configuration	31
3.3	Flow chart involving simulation and experimental approaches	33
3.4	Design process flow chart	34
3.5	Objective trees of PRS for Aludra SR-10 UAV	38
3.6	Components and function decomposition of PRS	41
3.7	Input and output of block system	42
3.8	Details function structure of Parachute Recovery System	43
3.9a	Single parachute system (at the middle of wing section) concept	45
3.9b	Two parachutes system (front and back) concept	46
3.9c	Two parachute system (left and right wing) concept	47
3.10	Flow domain for aircraft geometry model	55
3.11	Unstructured viscous grids around the aircraft	55

3.12	Conceptual design of inflated parachute	59
3.13	Flow domain and boundary condition for the parachute study	60
3.14	Unstructured viscous grids around the annular canopy	61
3.15	Unstructured viscous grids around the cruciform canopy	61
3.16	3D-view of Aludra SR-10 aircraft with annular parachute	63
3.17	3D-view of Aludra SR-10 aircraft with cruciform parachute	64
3.18	Flow domain and boundary condition for the parachute - aircraft combine study	64
3.19	Unstructured grids around the annular parachute -aircraft combine	65
3.20	Unstructured grids around the cruciform parachute -aircraft combine	66
3.21	A block diagram of an inertial navigation system (INS)	68
3.22a	Drop test block diagram system (LabView)	70
3.22b	Component connection for drop test system	71
3.23	Drop test system box	71
3.24	Servo motor (parachute) connection to autopilot	73
3.25	Parachute Parameter Setup	75
3.26	Summarize of parachute parameter setting	76
4.1	Velocity flow visualization around aircraft structure from	82
4.2	Static pressure distribution on the aircraft surface body	82
4.3	Velocity gradient for annular parachute	83
4.4	Velocity gradient for cruciform parachute	83
4.5	Drag coefficient variation against parachute size	84
4.6	Pressure distribution around annular parachute design	85
4.7	Pressure distribution around cruciform parachute design	86
4.8	Velocity flow structure around parachute recovery	88
4.9	Drag coefficient variation against parachute size	89
4.10	Static pressure distribution around parachute recovery (Annular canopy design)	90
4.11	Static pressure distribution around parachute recovery (Cruciform canopy design)	91

4.12	Dimension of modification design	94
4.13	Final conceptual design of PRS	95
4.14	PRS detailed design	96
4.15	Wing aircraft modification	97
4.16	Connection line between aircraft and parachute	97
4.17	Installation of parachute to the storage compartment	98
4.18	Complete parachute recovery system	98
4.19	Fixed propeller	99
4.20	Folding propeller	99
4.21	Original antenna position	100
4.22	New antenna position	100
4.23	Parachute inflation process	102
4.24	Average descent rate against time interval	102
4.25	Drop test landing point	105
4.26	Parachute recovery phase	107
4.27	Parachute inflation process during flight test	108
4.28	Calculation data and experimental data comparison chart	108

LIST OF TABLE

2.1	Rating of different types of recovery system	9
2.2	General application of hemisphere and cross canopy parachute	18
3.1	Aludra SR-10 unmanned aircraft specification	28
3.2	Lists of components for light control system	30
3.3	Evaluation scheme for design alternatives	44
3.4	Evaluation Matrices – Weighted rating method for parachute installation position	48
3.5	Evaluation Matrices – Weighted rating method for parachute design selection	50
3.6	Evaluation Matrices – Weighted rating method for parachute deployment system	51
3.7	Design parameter guideline	58
3.8	Annular parachute dimension data	59
3.9	Cruciform parachute dimension data	59
3.10	VN-200 Outputs in INS state (LLA)	68
4.1	Details of the unstructured grids around the aircraft result	80
4.2	Details of the unstructured grids around baseline parachute canopy	82
4.3	Details of the unstructured grids around canopy design	82
4.4	Simulation result of canopy design	84
4.5	Details of the unstructured grids around baseline parachute recovery	87
4.6	Details of the unstructured grids around parachute recovery system	87

4.7	Simulation result of parachute recovery system	89
4.8	Final conceptual design of parachute recovery system	93
4.9	Data collected from static drop tes4	105
4.10	Data collected from flight test	106



CONTENTS

DECLARATION	i
ACKNOWLEDGMENT	ii
ABSTRACT	iii
ABSTRAK	iv
LIST OF ABBREVIATIONS	v
LIST OF SYMBOL	vi
LIST OF FIGURE	vii
LIST OF TABLE	xi
CHAPTER 1: INTRODUCTION	
1.1 Project background	1
1.2 Problem statements	2
1.3 Objective of research	4
1.4 Scope of research	4
1.5 Contribution	5
1.6 Thesis organisation	6
CHAPTER 2: LITERATURE REVIEW	
2.1 Introduction	7
2.2 Recovery system for Unmanned Aerial Vehicle	7
2.3 Characteristic of parachute	9
2.4 Development of parachute recovery for UAV	13
2.5 Parachute parameter consideration	16
2.5.1 Canopy sizing	16
2.5.1.1 Annular parachute geometry	18
2.5.1.2 Cruciform parachute geometry	20
2.5.2 Parachute inflation time	21
2.5.3 Parachute inflation altitude loss	22

2.6	Application of Parachute Recovery System (PRS)	22
2.6.1	Cruciform Parachute Recovery System (PRS)	22
2.6.2	Hemisphere Parachute Recovery System (PRS)	23
2.6.3	Parafoils Parachute Recovery System (PRS)	25

CHAPTER 3: DESIGN METHODOLOGY

3.1	Introduction	27
3.2	Aludra SR-10 Unmanned Aerial Vehicle specification	28
3.3	Research method overview	31
3.4	Conceptual design	34
3.4.1	Define problem	35
3.4.2	Concept generation	39
3.4.2.1	Component decomposition	39
3.4.2.2	Function structure	41
3.5	Concept evaluation	43
3.5.1	Parachute installation position	44
3.5.2	Parachute design evaluation	48
3.5.3	Parachute deployment system evaluation	50
3.6	Numerical Simulation setup: Computational Fluid Dynamic (CFD).	52
3.6.1	Aerodynamic analysis of aircraft alone	53
3.6.2	Aerodynamic analysis of parachute alone	57
3.6.3	Aerodynamic analysis of recovery system (aircraft – parachute configuration)	63
3.7	Experimental approach	67
3.7.1	Static Drop Test	67
3.7.1.1	Impact Attenuation	72
3.7.2	Flight Test	73
3.7.2.1	Integrated deployment system	73
3.8	Mathematical modelling: Theory of landing position	77

CHAPTER 4: RESULT AND DISCUSSION

4.1	Introduction	79
4.2	Computational Fluid Dynamic (CFD) analysis	79
4.2.1	Aerodynamic analysis of aircraft alone	79
4.2.2	Aerodynamic analysis of parachute alone	82

4.2.3	Aerodynamic analysis of recovery system (aircraft – parachute configuration)	87
4.3	Final Conceptual Design	92
4.3.1	Airframe modification and system installation	97
4.3.2	Modification	99
4.4	Experimental result	101
4.4.1	Parachute static drop test	101
4.4.1.1	Parachute inflation behaviour	101
4.4.1.2	Drag coefficient analysis	103
4.4.1.3	Landing characteristics	103
4.4.1.4	Impact attenuation analysis	105
4.4.2	Flight test: System Evaluation	106

CHAPTER 5: CONCLUSION

5.1	Conclusion	113
5.2	Recommendation	114

REFERENCES

APPENDICES



CHAPTER 1

INTRODUCTION

1.1 Research background

Unmanned Aerial Vehicle (UAV) is an aircraft with no pilot on board. UAVs can be remotely controlled that can be flown by a pilot at a ground control station, (GCS) or autonomously based on pre-programmed flight plans. Over the past few decades, there have been significant researches and developments of UAVs. UAV can be distinguished from one another in terms of range or altitude, shapes, size, weight, endurance, design approach and missions [1]–[4]. UAV are now gaining high interests from civil and military fields to conduct a mission which includes reconnaissance, surveillance, target tracking, combat and high structure inspection. Moreover, UAVs have different components those are used to perform the mentioned missions and roles [2], [5], [6].

In military field, UAVs have been used not only for reconnaissance and surveillance but also as a target and decoy to simulate the profile of enemy aircraft or missile. Furthermore, UAVs can be employed in various areas including rescue, strike mission and combat for some high-risk missions. Multiple civilian roles have been designed for UAVs to be utilized in civil and numerous commercial applications such as search and rescue, survey, inspection, agriculture, aerial photography and data collection. Besides that, UAVs has also been widely used as experimental platform in various research groups in university and industry in order to develop further technologies [4], [7], [8].

Despite this rapidly grows industry of UAVs technology, safety to people and property remains as the utmost importance. The primary safety for Unmanned Aerial System (UAS) that closely relates to hazardous probability are: 1) a collision between UAV and other airspace users and 2) the controlled or uncontrolled impact of the UAV

crash on the ground, hit an object or structure or land on some undesired location [9]. Modern UAVs are equipped with a typically expensive and high technology electronic components. System failures and damage of UAVs whether it is structural or systems damage can be costly. To increase the safety of UAV operation, different types of UAV safety equipment can be adopted includes parachutes, nets, flight termination systems and emergency locator transmitters as recovery system [2], [5], [10].

The process of UAVs recovering is frequently described as the most difficult and critical phases in UAV operations. Proper design of recovery system for UAVs is highly desirable factor to prevent improper landing leads to accidents. However, different technologies for recovering commonly come together with positive and negative attributes. One mechanism that has been studied by several researchers in recent years to address safety concerns for most small type of UAV is by mounting a parachute system onto the aircraft. Not only as primary recovery method, but the parachute system can be the most effective method as a recovery system in the event of a system failure to reduce the risk on the aircraft and its payload.

The ultimate goal of this current research is to determine the feasibility and reliability of Parachute Recovery Systems (PRS) in order to allow small unmanned aerial vehicle (SUAVs) such as Aludra SR-10 UAV safe landing without damage. Thus, a proper development of mechanism and solutions are required to allow vertical descent and horizontal landing of aircraft in preventing the damage on aircraft's airframe and structure. This study approaches to promote the systematic design technique and process of parachute recovery including the analysis of its performance. Besides, these researches are beneficial to predict the landing area of these aircraft using the parachute recovery system.

1.2 Problem statements

Unmanned Systems Technology (UST) Aludra SR-10 Unmanned Aerial Vehicle (UAV) was purposely designed for survey and mapping mission. In the early designing stage of Aludra SR-10 UAV, this type of unmanned aircraft used skid and belly landing as a recovery method. This type of landing method may encounter a tough landing on hard soil and gravel, producing high impact momentum on the aircraft body. This impact may cause structural or system damage which costly to be repaired. Therefore, this research disclosure was performed in a correlation to

enhancements in the field of aircraft safety and implementation of emergency parachute recovery for Aludra SR-10 UAV.

Nowadays, Parachute Recovery System (PRS) are recently used for landing method purposely to replace the belly landing technique. The PRS mechanism are currently applied in numerous tasks in aviation industry and very suitable to be applied as recovery system in small and medium sized unmanned aircraft such as Aludra SR-10 UAV. To date there are various embodiments and concepts correspond to the parachute recovery which are significantly important be considered for the investigation. However, previous studies of the PRS for UAV lack several conceptual and methodological analyses. The criteria includes parachute canopy shape, attachment to the aircraft, deployment compartment, deployment mechanism and others.

There are four shapes of commonly used parachute canopies UAV's recovery system. These four types of parachute canopies are cruciform, hemisphere, annular and parafoil shape. Different type of parachute design produce different drag forces during descending. The parachute which produce provide a higher drag force will give better performance in parachute recovery system [11], [12]. A significant study of drag force produced by different shapes of parachute can be determined using Computational Fluid Dynamic (CFD).

Upon an activation of the deployment mechanism, the parachute should rapidly deploys away from the storage compartment. The ability to rapidly deploy the parachutes is an important feature for low flying aircraft such as Aludra SR-10 UAV which is necessary in order to minimize the altitude loss. Further investigations are needed to explore the mechanism that allows the parachute to deploy rapidly after being activated. A static drop test could provide a needed information in determining the parachute inflation process and descending behaviour, as well as the minimum deployment altitude.

Mostly, the parachute descends uncontrollably and almost slightly vertically through the air stream. This situation leads to an uncertain landing point. Investigation of the landing area or range is considered as a continuing concern within the parachute recovery performance. The main challenge faced by many researchers is to predetermine the recovery area of an aircraft from the parachute deployment point. An analysis from the flight test data is useful to determine the accuracy of landing area prediction.

Additional weight to the aircraft is an important concept in the most studies. Additional weight is an impact factor that significantly affect the flight performance of UAV which include its stability, slower cruising speeds and reduced aircraft endurance. Therefore, the addition of significant weight from parachute recovery equipment and devices to the UAV should be considered. In this study, the design criteria for these recovery system were set to lift a maximum payload of the aircraft up to a maximum take-off weight (MTOW) of 5 kg.

1.3 Research objectives

This prospective study was designed to investigate the use of parachute recovery as a landing method for CTRM research unmanned aircraft, Aludra SR-10 UAV. The specific objective of this study were

- i. To design a suitable parachute for Aludra SR-10 UAV as the Parachute Recovery System (PRS).
- ii. To develop and manufacture a complete Parachute Recovery System (PRS) for Aludra SR-10 UAV.
- iii. To conduct a static drop test and flight test in order to investigate the performance of the design Parachute Recovery System (PRS).

1.4 Scope of study

To achieve the research objective as discussed in the previous sub chapter, the full scopes of study will be conducted in this research work involves:

- i. **Understanding on the use of CFD ANSYS-Fluent software:** The ANSYS Fluent software is CFD software which developed based on Time Reynolds Average Navier Stokes Equations (TRANS). To solve this type equations, there are three elements need to be considered. These three elements are (1) numerical grid generation, (2) numerical scheme used for solving the TRANS (Flow solver), and (3) the turbulence models. The ANSYS software allows various grid model can be implemented (course, medium and fine), various flow solver and various turbulent model can be implemented. Through understanding on ANSYS software helps in solving the flow problems involving parachute.

- ii. **Static drop test:** The test was conducted to evaluate a parachute performance through releasing the parachute from altitude of 38 meter above ground level (AGL) under 5kg payload. The on board system measurement unit were designed to evaluate the parachute performance includes the rate of descent and the stress impact. This system consist of NI myRio, IMU and GPS devices were developed using LabVIEW software.
- iii. **Manufacturing and installation of PRS:** Installation of PRS into Aludra SR-10 UAV involved only a simple modification to the UAV airframe and system. The detailed mechanism involved in implementing the design of parachute recovery were based on the design evaluation and concept selection in the design process.
- iv. **Flight test:** The performance characteristics of PRS included parachute inflation time, descent time taken, deployment distance, PRS reliability and deployment method verification were observed and analysed. The landing distance area during flight test was compared and validated with the mathematical model of prediction landing area.

1.5 Contribution

The design, manufacturing and test the Recovery Parachute System on the Aludra SR-10 UAV represent the research work which will give contribute as follows:

- i. Deeper understanding of the Parachute Recovery System (PRS), and also the selection of suitable deployment system and mechanisms for Aludra SR-10 UAV.
- ii. Provide a useful knowledge to identify, select and design the suitable type of parachute canopy to be used as parachute for recovery system.
- iii. The static drop test procedure represent a suitable test for evaluating the rate of descent parachute and stress impact.
- iv. The development of flight testing process gives a real performance of the capability and reliability of parachute recovery system.

1.6 Thesis organization

The overall structure of the study was divided into five chapters.. The first chapter described research background, problem statements, objective and scope of the study. Chapter 2 focused on laying out the theoretical background and previous work by the researchers from the earliest models to the latest models related to the parachute recovery systems. The information was collected from several resources and then was then reviewed to obtain related data regarding the design requirement and consideration for the parachute recovery.

The third chapter explained the research methodology employed for this study. The methodological approach was performed in this study involved computational simulation and experimental approach. The simulation approach was conducted by Computational Fluid Dynamic (CFD), meanwhile the experimental approach involved a static drop test and an open environment flight test. This chapter described the design methodology approach in the early phase of the design process development, provided with the outline function, set of integrated ideas and concepts.

The fourth section presented the findings of the research, focusing on the three key themes that were (i) computational simulation, (ii) drop test and flight test, and (iii) addresses of each research question in turn. The results obtained from CFD aerodynamic simulation offered an important contribution to the selection of parachute canopy design. The selected parachute undergone a drop test to determine the feasibility and ability to support load during the landing before undertaking into the final testing. In the final test, the flight test assisted in determining mechanical feasibility of the parachute recovery for Aludra SR-10 UAV. Lastly, final chapter summarized the current findings in order to reflect on the extent to which this study was contributed to the parachute recovery study and provided basics idea for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It is very important to obtain necessities on the subject matter knowledge as can contribute to a proper execution of the research. The concept and modelling technique for this system was also highlighted.

2.2 Recovery system for Unmanned Aerial Vehicle

Recovery are often described as the most difficult and critical phases in UAV operations. The primary function of the recovery system is to land the UAV on a runway, smooth field road, or carrier deck safely. Proper and suitable design of the recovery system for UAVs is highly desirable factor to prevent improper landing that may lead to accidents. There are various types of recovery system that available for the small-to-medium UAVs such as skid or belly recovery, wheeled landing, parachute recovery and vertical-net recovery. However, different technologies for recovering present together with positive and negative attributes [2], [4], [5], [13].

The simplest and less expensive option for the recovery system is skid and belly landing method, where the aircraft's fuselage contacts directly to the ground. This recovery method normally may damage the aircraft's structure due to a sudden impact force thus, increases the maintenance and repairing cost. Therefore, a strong belly structure along with shock absorbers is required to withstand the impact.

A conventional landing is also known as wheeled landing and has been used by many small-to-medium UAVs due to their gentle retrieval and smooth landing. This type of recovery system can protect the aircraft from damage during landing while the landing gear act as a shock absorbent. In addition, the landing gear can provide a more

stable support for the aircraft on the ground compared to the skid or belly landing recovery. However, this type of recovery requires a large landing area and cannot be applied when there is no or less availability of adequate landing area.

The parachute recovery is commonly used by a small and air-launched unmanned aircraft as recovery system and also as an emergency flight termination system. Numerous parachute configuration have been designed to have a relatively low rate of descent in order to decrease the damage of aircraft upon the impact toward the ground or water. The landing position of the UAVs after parachute deployment is difficult to be determined due to difficulty of directional to control because it is subjected to the vagaries of the wind. Therefore, the parachute deploys at a very low altitude in order to reduce a drift distance.

Vertical-net recovery is the most commonly used approaches for "zero-length" recovery method. A net is gripped tightly around two balancing poles that are staked firmly onto the ground. This type of recovery system is most desirable because the forces are properly distributed to the entire aircraft, so that the UAV does not get damage. An important criterion of using this type of recovery system is the location of the propeller as it is directly contacted between propeller and net may damage.

Abinaya and Arravind [13] have compared various types of recovery system for the small-to-medium AVs in term of safety, cost, design complexity, operator skill and recovery failure rate. Table 2.1 expresses the rating between four types of recovery methods used by the SUAVs such as skid or belly recovery, wheeled landing, parachute recovery and vertical-net recovery. This rating comparison help is beneficial identify and select an effective recovery design for Aludra SR-10 UAV. Apparently, according to the rating comparison by considering the advantages and disadvantages of every system, the PRS can fulfill the requirement for a successful recovery method. This type of recovery method allows a soft landing even with it is handled by an untrained operator

Table 2.1: Rating of different types of recovery system

Classification	Skid or belly landing	Wheeled landing	Parachute recovery	Vertical-net recovery
Cost	Low	High	Medium	High
Safety	Medium	High	Medium	Average
Operator skill requirement	Low	Average	Average	Medium
Design complexity	Low	High	Medium	Medium
Recovery failure rate	Medium	Low	Medium	High

2.3 Characteristic of parachute

Modern designs of parachutes are classified into two categories that are ascending and descending canopies. An ascending canopy is specifically built to ascend and stay aloft as long as possible such as paraglide. In contrast, the descending canopy provides a reduced/ low amount of dragging force. This condition is mainly to slow and maintain a balance of dropping object or person so that the item would remain safe until it reaches the ground [14].

The physics behind deployment parachute is involving the interaction between gravity and air resistance includes several factors such as weight and shape of the parachute. As the aircraft's power supply was cut off, no thrust is produced thus leads to zero thrust acting on the aircraft. An explosive charge is widely used to deploy the parachute in order to slow down the descent rate of the aircraft. Figure 2.1 shows the forces act on the parachute during the recovery system. Since a weight still act on the aircraft, the aircraft immediately falls back to the earth by its weight. Air resistance increases due to a large surface area that is produced by canopy when it is opened. As the aircraft descends, the drag and the weight in opposing forces are produced. The weight (W) is always directed towards the centre of the earth while the drag force (D) is opposed to the motion direction. A stable parachute is descent in equilibrium acceleration between the total drag of the parachute and the aircraft (D_T) and the weight of the load and the parachute assembly (W_T).

REFERENCES

- [1] M. H. Sadraey, *Aircraft Design: A Systems Engineering Approach*. John Wiley & Sons, 2012.
- [2] P. G. Fahlstrom and T. J. Gleason, *Introduction to UAV Systems, Fourth Edition*. Chichester, UK: John Wiley & Sons, Ltd, 2012.
- [3] R. Austin, *Unmanned Aircraft Systems: UAVS Design, Development and Deployment*. John Wiley & Sons, 2011.
- [4] R. W. Beard and T. W. McLain, *Small Unmanned Aircraft: Theory and Practice*. Princeton University Press, 2012.
- [5] J. Gundlach, *Designing Unmanned Aircraft Systems: A Comprehensive Approach*. American Institute of Aeronautics & Astronautics, 2014.
- [6] F. Kendoul, "Survey of Advances in Guidance, Navigation, and Control of Unmanned Rotorcraft Systems," *J. F. Robot.*, vol. 29, no. 2, pp. 315–378, Mar. 2012.
- [7] G. Cai, B. M. Chen, and T. H. Lee, *Unmanned Rotorcraft Systems*. Springer Science & Business Media, 2011.
- [8] S. S. Shamsudin and X. Chen, "Recursive Gauss-Newton based training algorithm for neural network modelling of an unmanned rotorcraft dynamics," *Int. J. Intell. Syst. Technol. Appl.*, vol. 13, no. 1/2, p. 56, 2014.
- [9] R. Clothier and R. A. Walker, *Handbook of unmanned aerial vehicles*, no. January. 2015.
- [10] K. Draganová, V. Moucha, and František KMEC, "Safety Equipment And Emergency Procedures For Uav Control," in *Proceedings of the International Scientific Conference Modern Safety Technologies in Transportation 2013*, 2013.

- [11] K. Stein, T. E. Tezduyar, V. Kumar, S. Sathe, R. Benney, E. Thornburg, C. Kyle, and T. Nonoshita, "Aerodynamic Interactions Between Parachute Canopies," *J. Appl. Mech.*, vol. 70, no. 1, p. 50, 2003.
- [12] D. J. Cockrell, *The Aerodynamics of Parachutes*. North Atlantic Treaty Organization, Advisory Group for Aerospace Research & Development, 1997.
- [13] R. Abinaya and R. Arravind, "Selection of low-cost recovery system for Unmanned Aerial Vehicle," *Int. Res. J. Eng. Technol.*, vol. 4, no. 5, pp. 1074–1078, 2016.
- [14] T. Wyllie, "Aircraft Engineering and Aerospace Technology Parachute recovery for UAV systems," *Aircr. Eng. Aerosp. Technol.*, vol. 73, no. 6, pp. 542–551, 2001.
- [15] T. W. Knacke, *Parachute Recovery Systems Design Manual*. Naval Weapons Center, 1991.
- [16] K. G. S. Cartwright, "Feasibility of Parachute Recovery Systems for Small UAVs," University of New South Wales, Canberra, Australia, 2008.
- [17] K. G. S. Cartwright, "Parachute Recovery System for Small Research UAV's," University of New South Wales, 2008.
- [18] Tristan Foon, "RDTE of Parachute Recovery System for ADFA UAV," University of New South Wales, 2009.
- [19] W. B. Andrew, "RDTE a Parachute Recovery System for a UAV," University of New South Wales, 2011.
- [20] G. Nicolas, "Parachute Recovery Systems for Unmanned Aerial Vehicles," Swiss Federal Institute of Technology Zurich, 2009.
- [21] G. Nicolas, "Desinging a Parachute Recovery System for the ASL Solar Airplane," Swiss Federal Institute Technology Zurich, 2010.
- [22] P. H. Donald and P. H. Michael, "Precision Parachute Recovery System," US 6,416,019 B1, 2002.
- [23] L. M. Nicolai, R. R. William, and J. R. Douglas, "Autonomous Payload Recovery System," US 6,808,144 B1, 26-Dec-2002.
- [24] Ç. Fatma and E. Bestem, "Parachute Fabric and Its Manufacturing Process," *Int. J. Sci.*, vol. 6, no. 5, 2017.
- [25] J. S. Duncan, Ed., *Parachute Rigger Handbook*. Federal Aviation Asministration, 2015.

- [26] Ronen Nadir, "Parachute release device for unmanned aerial vehicle (UAV)," US 8,191,831 B2, 2012.
- [27] M. G. Shaun and C. R. Harley, "Parachute deployment apparatus, system and method of use," US 2017/0066537 A1, 08-Sep-2017.
- [28] L. Wang, D. J. Bodenstein, R. M. Welsh, and K. I. McWilliams, "Parachute deployment system for an unmanned aerial vehicle," US 2017/0225792 A1, 2017.
- [29] U. Srivastava and A. S. Verma, "Design and Simulation of Autonomous Parachute System for Unmanned Aerial Vehicle," *Int. J. Adv. Eng. Res. Dev.*, vol. 5, no. 6, 2018.
- [30] S. Randall, "Parachute Sizing Chart," *UKHAS wiki*. UK High Altitude Society, 2001.
- [31] Galaxy GRS, "Recovery system for parachute," *Galaxy Holding s.r.o*, 2012. [Online]. Available: <https://www.galaxysky.cz/how-to-choose-a-ballistic-recovery-system-s3-en>. [Accessed: 26-Aug-2017].
- [32] *Air international.*, vol. 74, no. 4. Fine Scroll Ltd, 1974.
- [33] UKR SpecSystem, "PD-1 Unmanned Aerial System," 2014.
- [34] Air Affairs Australia, "Phoenix Jet UAV Target Drone," 2015.
- [35] Polish Air Force Institute of Technology, "ZOCP-JET2 target drone," *Polish Air Force Institute of Technology*, 2016. [Online]. Available: <http://www.defence24.com/472180,jet-2-target-drone-tests-jet-propelled-uav-developed-by-the-polish-air-force-institute-of-technology-in-the-air-wideo>. [Accessed: 13-Jan-2017].
- [36] Tuffwing, "TuffWing UAV Mapper - Aerial Mapping Drone," 2015.
- [37] Australian Defence Force, *I-View UAV*. Australian Defence Force, 2006.
- [38] Unmanned Systems Technology Sdn Bhd, "ALUDRA SR-10," 2015.
- [39] G. E. Dieter and L. C. Schmidt, *Engineering design*. McGraw-Hill Higher Education, 2009.
- [40] Ballistic Recovery Systems Inc., "General Installation Guide for BRS-6™ Emergency Parachute Recovery Systems," 2008.
- [41] D. Feszty and T. Jakubík, "NGM_JF006_1: Computational Fluid Dynamics," 2017.
- [42] F. R. Menter, "Zonal Two Equation k-omega, Turbulence Models for Aerodynamic Flows," *24th Fluid Dyn. Conf.*, 1993.

- [43] W. L. Oberkampf and T. G. Trucano, "Verification and Validation in Computational Fluid Dynamics," 2002.
- [44] H. (Hendrik) Tennekes and J. L. (John L. Lumley, *A first course in turbulence*, 14. print. Cambridge, Mass. [u.a.]: MIT Press, 1972.
- [45] Department of Defense (DoD), "System Safety: Environment, Safety, and Occupational Health Risk Management Methodology for Systems Engineering," United States of America, 2010.
- [46] A. Panta, S. Watkins, and R. Clothier, "Dynamics of a Small Unmanned Aircraft Parachute System," *J. Aerosp. Technol. Manag*, 2017.
- [47] Z. Jin, S. Pasqualini, and Z. Yang, "Experimental investigation of the flow structures in the wake of a cross parachute canopy," *Eur. J. Mech. B/Fluids*, vol. 60, pp. 70–81, 2016.
- [48] Robert Habbit III, "Computational Analysis of Turbulent Flow Around NACA 4412 Airfoil with Open Source CFD Software," The University of New Mexico, 2015.
- [49] M. Omolayo Petinrin and V. A. Onoja, "Computational Study of Aerodynamic Flow over NACA 4412 Airfoil," *Br. J. Appl. Sci. Technol.*, vol. 21, no. 3, p. 31893, 2017.
- [50] B. Navin Kumar, K. M. Paramasivam, M. Prasanna, and A. Z. G. Mohamet Karis, "Computational Fluid Dynamics Analysis of Aerodynamic Characteristics of Naca 4412 Vs S809 Airfoil for Wind Turbine Applications," *Int. J. Adv. Eng. Technol.*, vol. 7, no. 3, pp. 168–173, 2016.
- [51] H. K. Versteeg and W. Malalasekera, *An introduction to computational fluid dynamics : the finite volume method*. Pearson Education Ltd, 2007.
- [52] Y. Cao, K. Wang, and J. Sheridan, "Numerical simulation of parachute Fluid-Structure Interaction in terminal descent," *Sci. China Technol. Sci.*, vol. 55, no. 11, pp. 3131–3141, 2012.
- [53] M. Dawoodian, Abdolrahman Dadvand, and M. Hassanzadeh, "A Numerical and Experimental Study of the Aerodynamics and Stability of a Horizontal Parachute," *ISRN Aerosp. Eng.*, p. 8, 2013.
- [54] K. Stein, R. Benney, T. Tezduyar, V. Kalro, J. Potvin, and T. Bretl, "Fluid-structure interaction simulation of a cross parachute- Comparison of numerical predictions with wind tunnel data," in *CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference, 15 th, Toulouse, France*, 1999, pp. 172–181.

- [55] Q. Hou and Z. Zou, "Comparison between Standard and Renormalization Group k- ϵ Models in Numerical Simulation of Swirling Flow Tundish," *ISIJ Int.*, vol. 45, no. 3, pp. 325–330, 2005.
- [56] A. Bakker, "Applied Computational Fluid Dynamics," 2001.
- [57] M. Pavlovich Bulat and P. Victorovich Bulat, "Comparison of Turbulence Models in the Calculation of Supersonic Separated Flows," *World Appl. Sci. J.* 27, vol. 27, no. 10, pp. 1263–1266, 2013.
- [58] K. R. Stein, R. J. Benney, T. E. Tezduyar, J. Leonard, and M. L. Accorsi, "Fluid-Structure Interactions of a Round Parachute: Modeling and Simulation Techniques," *J. Aircr.*, vol. 38, no. 5, 2001.
- [59] Oliver J. Woodman, "An introduction to inertial navigation," 2007.
- [60] VectorNav Technologies, "Vectornav: VN-100 User Manual," 2009.
- [61] National Instruments, "User Guide and Specifications: NI myRIO-1900," 2013.
- [62] National Instruments, "LabVIEW: Getting Started with LabVIEW," 2013.
- [63] ArduPilot, "Failsafe Mechanisms: Parachute," *ArduPilot Dev Team.*, 2015.
[Online]. Available: <http://ardupilot.org/copter/docs/parachute.html>.
[Accessed: 30-Aug-2017].
- [64] G. Klimi, *Exterior ballistics with applications : skydiving, parachute fall, flying fragments*. Xlibris Corporation, 2008.
- [65] A. Abbas-Bayoumi and K. Becker, "An industrial view on numerical simulation for aircraft aerodynamic design," *J. Math. Ind.*, vol. 1, no. 1, p. 10, Dec. 2011.
- [66] G. Xing long, Z. Qing bin, T. Qian gang, and Y. Tao, "Fluid-Structure Interaction Simulation of Parachute in Low Speed Airdrop," in *Proceedings of the World Congress on Engineering 2013*, 2013, vol. 3.
- [67] D. Crocker, *Dictionary of aeronautical English*. New York: Fitzroy Dearborn, 1999.